

Light Color-Octet Scalars at the LHC

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Outline

- ⦿ extend SM scalar sector
 - $(8,2)_{1/2}$ color-octet scalar
- ⦿ motivation
 - bottom-up (minimal flavor violation)
 - top-down (SU(5) GUT)
- ⦿ octet scalar phenomenology at the LHC
 - single charged octet production
 - neutral octet mediated $t\bar{t}$ production

Bottom-up (Minimal Flavor Violation)

- absence of flavor-changing neutral currents – new physics should obey principle of Minimal Flavor Violation
- principle of MFV – flavor structure of physics beyond SM should be completely determined by SM Yukawa structure
- extend SM scalar sector to include $(8,2)_{1/2}$ color octet [\(Manohar & Wise\)](#)

$$\mathcal{L}_Y = \bar{d}_R \Gamma_D S^\dagger Q_L + \bar{u}_R \Gamma_U Q_L^\alpha S^\beta \epsilon_{\alpha\beta} + \text{h.c.}$$

- assume MFV – $\Gamma_U = \eta_U Y_U$ & $\Gamma_D = \eta_D Y_D$
 - η_U & η_D parameterize scalar coupling strength to matter
- in physical basis with new scalar states: S_I , S_R , S^+ , S^-

$$\begin{aligned}\mathcal{L}_Y^{\text{MFV}} = & \frac{\sqrt{2}}{v} \bar{d} \left(P_L \eta_D m_D V_{\text{CKM}} - P_R \eta_U V_{\text{CKM}}^\dagger m_U \right) S^- u \\ & + \frac{\sqrt{2}}{v} \bar{u} \left(P_R \eta_D V_{\text{CKM}}^\dagger m_D - P_L \eta_U m_U V_{\text{CKM}} \right) S^+ d \\ & + \eta_D \frac{m_D}{v} S_R^0 \bar{d} d + \eta_U \frac{m_U}{v} S_R^0 \bar{u} u + i \eta_D \frac{m_D}{v} S_I^0 \bar{d} \gamma_5 d - i \eta_U \frac{m_U}{v} S_I^0 \bar{u} \gamma_5 u\end{aligned}$$

Top-down (Adjoint SU(5) GUT)

- Renormalizable Adjoint SU(5) GUT (Fileviez Pérez)
 - Matter: $\bar{5}$, 10, 24; Gauge: 24_G
 - Higgs: 5_H , 24_H , 45_H
- naturally predicts colored octet scalar (45_H)
 - SM flavor structure

$$-S_{Yukawa} = \int d^4x \left(Y_1 10 \bar{5} 5_H^* + Y_2 10 \bar{5} 45_H^* + Y_3 10 10 5_H + Y_4 10 10 45_H \right) + \text{h.c.}$$

- SM charged fermion masses

$$M_D = Y_1 \frac{v_5^*}{\sqrt{2}} + 2 Y_2 \frac{v_{45}^*}{\sqrt{2}}$$

$$M_E = Y_1^T \frac{v_5^*}{\sqrt{2}} - 6 Y_2 \frac{v_{45}^*}{\sqrt{2}}$$

$$M_U = 4(Y_3 + Y_3^T) \frac{v_5}{\sqrt{2}} - 8(Y_4 - Y_4^T) \frac{v_{45}}{\sqrt{2}}$$

Connecting Bottom-up & Top-down

- color octet and matter interactions

$$\bar{d}_R \frac{(M_E - M_D^T)}{2\sqrt{2}v_{45}^*} S^\dagger Q_L \& \bar{u}_R 8(Y_4^T - Y_4) Q_L^\alpha S^\beta \epsilon_{\alpha\beta}$$

- rewrite Γ_U , Γ_D couplings from MFV scenario

$$\Gamma_U = 8(Y_4^T - Y_4) \& \Gamma_D = \frac{M_E - M_D^T}{2\sqrt{2}v_{45}^*}$$

- ηU & ηD probe GUT properties

$$\eta_D = \frac{v}{4v_{45}^* m_b} (m_\tau - m_b)$$

- proton decay, gauge unification (Fileviez Pérez, et al)
 - $m_S < 4.4 \times 10^5$ GeV
- with upper bound, color octet could be light
 - good chance for production at LHC
 - extract information about GUT properties

Color Octet Scalar Phenomenology

- ⦿ focus on single color octet scalar production at the LHC
 - take scalar mass $m_s = 1 \text{ TeV}$
- ⦿ single charged octet scalar production
 - model dependent
 - > insight to η_U & η_D (GUT properties)
 - probe of u-d-scalar Yukawa coupling
 - > analogous to single top production (V_{tb})
- ⦿ neutral octet scalar mediated top pair production
 - model dependent
 - > channel opens for large η_D

Single Scalar Production Phenomenology

- ⦿ octet scalars decay to heavy quarks
- ⦿ cascade decays ($S^+ \rightarrow W^+ S^0$, $S_L \rightarrow Z S_R$) unlikely
 - scalar mass split by electroweak symmetry breaking
 - mass splitting is small, constrained by Higgs quartic coupling
- ⦿ two scenarios
 - $\eta_U \sim 1$, $\eta_D \sim 1$
 - > only single charged octet production feasible
 - $\eta_U \sim 1$, $\eta_D \sim 40$
 - > single charged octet production enhanced
 - > neutral octet mediated top pair production opened

Single S^\pm Production

- ⦿ single charged octet production $gb \rightarrow S^- t$ & $g\bar{b} \rightarrow S^+ \bar{t}$
- ⦿ $\eta_U, \eta_D \sim 1$
 - m_U coupling dominates
- ⦿ $\eta_U \sim 1, \eta_D \sim 40$
 - $\sigma(S^\pm \text{ production})$ enhanced
- ⦿ BR: $S^+ \rightarrow tb \sim 100\%$
 - scalar cascade decays suppressed
- ⦿ LO Events
 - signal: $\sigma_{LO} \approx 93 \text{ fb}$ ($\eta_D \sim 1$), $\sigma_{LO} \approx 123 \text{ fb}$, ($\eta_D \sim 40$)
 $pp \rightarrow S^+ \bar{t} \rightarrow t\bar{t}b$ & $pp \rightarrow S^- t \rightarrow t\bar{t}\bar{b}$
 - backgrounds: $t\bar{t} + \text{jet}$ ($\sigma_{LO} \approx 526 \text{ pb}$), W+jets, QCD
 $pp \rightarrow t\bar{t}j$
 - generated using MadEvent
 - > with standard acceptance cuts

Detector 'Simulation'

- ⦿ gaussian smearing of E or p_T
 - jet-like objects (b-quark, light quarks, gluon)
$$\frac{\delta E}{E} = \frac{0.8}{\sqrt{E/\text{GeV}}} \oplus 0.03$$
 - electrons
$$\frac{\delta E}{E} = \frac{0.1}{\sqrt{E/\text{GeV}}} \oplus 0.007$$
 - muons
$$\frac{\delta p_T}{p_T} = 0.15 \frac{p_T}{\text{TeV}} \oplus 0.005$$
 - missing E_T defined by momentum balancing
- ⦿ 'jet' algorithm - iteratively combine final state partons with
$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$$
 - combined object tagged as jet
- ⦿ b-tag eff = 60%, fake rate = 3% (study sensitive to fake rate)

Top Reconstruction

- ⦿ only keep pure hadronic or single lepton (e or μ) events
- ⦿ expect final state partons to be highly boosted
 - top decays highly collimated
- ⦿ semi-leptonic top decay
 - find jet with smallest $\Delta R_{jet,lep} < \Delta R_{max} = 0.6$
 - combine lepton and missing energy
 - > W mass constraint to find longitudinal component
 - solve ambiguity by picking solution which gives smaller $\Delta R_{jet,W}$
 - tag as top-jet if $m_{jet,W}$ falls within 171 ± 50 GeV

Top Reconstruction

- ⦿ hadronic top decay
 - find two jets with smallest $\Delta R_{jet,jet} < \Delta R_{max} = 0.8$
 - if $m_{jet,jet}$ falls within m_{top} window, tag as top
 - if $m_{jet,jet}$ falls within m_W window, 40-121 GeV, temporarily tag as W
 - > find jet with smallest $\Delta R_{W_temp,jet} < \Delta R_{max} = 0.8$
 - > if $m_{W_temp,jet}$ falls within m_{top} , tag as top
- ⦿ algorithm continues until no further tops found

Single Charged Octet Production - Analysis

cuts

- kinematics & 'shape' (Mercedes Benz)

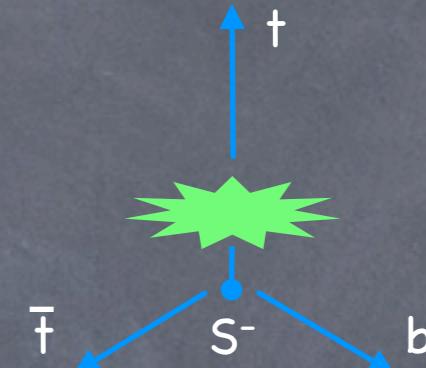
Cuts	$S_l/\sqrt{B_l}$	S_l/B_l	$S_{l+h}/\sqrt{B_{l+h}}$	S_{l+h}/B_{l+h}	
$H_T > 1000 \text{ GeV}$	5.52	0.0063	8.89	0.0062	$S_l, B_l = \text{semi-leptonic signal \& background events}$
$\exists t_1, t_2, b_1$	0.95	0.0096	1.92	0.0099	
$900 < M_{t_1, b_1} < 1100 \text{ GeV}$	2.60	0.12	5.93	0.16	$S_{l+h}, B_{l+h} = \text{combination of semi-leptonic and fully hadronic events}$
$\Delta R_{t_1, b_1}, \Delta R_{t_2, b_1} < 3.0$	3.60	0.32	8.82	0.47	
$\cos\theta_{t_1, b_1} < 0.5, \cos\theta_{t_2, b_1} < 0.7$	4.56	0.62	10.3	0.73	

- 300 fb^{-1} of integrated luminosity
- for 5σ significance
 - semi-leptonic: $> 300 \text{ fb}^{-1}$
 - semi-leptonic + hadronic $< 100 \text{ fb}^{-1}$

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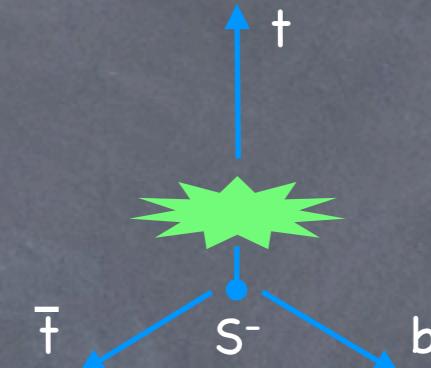
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Analysis

- Estimate of error on measurement

- error on $|\eta_D|^2$ & $|\eta_U|^2$ - connection to GUTs

$$\frac{\delta S}{S} = \frac{\sqrt{S + B}}{S} \oplus F_S S \oplus F_B B$$

- F_S, F_B theoretical errors for signal and background

- LO variation in σ_S & σ_B by scale variation $0.5\mu_F$ & $2\mu_F$

$F_{S,LO} \approx \pm 15\%$ & $F_{B,LO} \approx \pm 40\%$ $(\mu_F, \text{ factorization scale})$

\circlearrowleft background improved with NLO calculations & off peak data study	F_S	F_B	$\delta \eta_U ^2/ \eta_U ^2$ (semi) $\eta_U=1$	$\delta \eta_U ^2/ \eta_U ^2$ (all) $\eta_U=1$	$\delta \eta_U ^2/ \eta_U ^2$ (semi) $\eta_U=2$	$\delta \eta_U ^2/ \eta_U ^2$ (all) $\eta_U=2$
	0	0	0.28	0.14	0.10	0.05
	0.05	0.10	0.33	0.19	0.12	0.08
	0.05	0.20	0.43	0.31	0.14	0.10
	0.10	0.10	0.34	0.21	0.15	0.12
	0.10	0.20	0.44	0.32	0.16	0.13
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S_I & S_R Mediated Top Pair Production

- neutral octet scalar mediated top pair production

$$b\bar{b} \rightarrow S_I, S_R \rightarrow t\bar{t}$$

- channel opens with sizable η_D , take $\eta_D \sim 40$
- scalar cascade decays suppressed

- LO Events

- signal: $\sigma_{LO} \approx 289$ fb

$$pp \rightarrow S_I, S_R \rightarrow t\bar{t}$$

- backgrounds: $t\bar{t}$ ($\sigma_{LO} \approx 640$ pb), W+jets, QCD

$$pp \rightarrow t\bar{t}$$

- $t\bar{t}$ becomes the dominant background after preselection cuts (CMS, ATLAS)

- similar generation and simulation as before

- semi-leptonic top reconstruction: $\Delta R_{max} = 0.8$
- hardronic top reconstruction: $\Delta R_{max} = 1.1$

Analysis

- ⦿ cuts
 - kinematics

Cuts	$S_l/\sqrt{B_l}$	S_l/B_l	$S_{l+h}/\sqrt{B_{l+h}}$	S_{l+h}/B_{l+h}
$H_T > 900 \text{ GeV}$	6.0	0.024	12.7	0.025
$\exists t_1, t_2$	3.2	0.021	8.8	0.023
$950 \text{ GeV} < M_{t_1,t_2} < 1050 \text{ GeV}$	5.3	0.074	15.1	0.083

- ⦿ discovery at 100 fb^{-1} of integrated luminosity
- ⦿ large uncertainty due to large B/S
- ⦿ need to understand backgrounds

F_B	$\delta\eta_{bb}/\eta_{bb}$ (semi)	$\delta\eta_{bb}/\eta_{bb}$ (all)
0	0.20	0.07
0.01	0.24	0.14
0.025	0.39	0.31
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Conclusions

- ⦿ $(8,2)_{1/2}$ extension to scalar sector
 - preserves MFV
 - insight to GUT properties via η_U & η_D
- ⦿ phenomenology
 - single charged octet scalar production
 - > semi-leptonic only events requires $> 300 \text{ fb}^{-1}$
 - > large S/\sqrt{B} at 300 fb^{-1} for combined events
 - neutral octet mediated top-pair production
 - > semi-leptonic alone statistically significant at 100 fb^{-1}
 - > large S/\sqrt{B} at 100 fb^{-1} , using combined semi-leptonic and hadronic events (provided η_D is large)
 - backgrounds need to be well understood to estimate error on measurements